

Dynamics of Boundary Currents and Marginal Seas

Dr. William E. Johns
Rosenstiel School of Marine and Atmospheric Science
Division of Meteorology and Physical Oceanography
University of Miami,
4600 Rickenbacker Causeway Miami, FL 33149-1098
Telephone: 305/361-4054, Fax 305/361-4696
wjohns@rsmas.miami.edu

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LONG TERM GOALS

To describe and understand the dynamics of ocean circulation, with emphasis on western boundary current systems and interactions between the oceans and marginal seas.

OBJECTIVES

Research during the past year has been focused on observational studies of the exchange between the northwestern Indian Ocean and its bordering marginal seas: the Red Sea and the Arabian (Persian) Gulf. Extensive time series observations collected between May 1995 and November 1996 in the Bab el Mandeb Strait at the entrance to the Red Sea, in collaboration with Dr. Steve Murray of LSU, were analyzed to determine the annual cycle of water exchange through the strait and the dynamics of seasonal and synoptic scale variations in the Strait flow. Time series observations were also collected in the Strait of Hormuz from December 1996 to March 1997 to obtain a first direct measurement of the annual variation in deep outflow from the Persian Gulf to the Arabian Sea.

APPROACH

Measurements collected in these programs consist of moored time series observations of currents using profiling (ADCP) and conventional current meters, and of water properties using temperature/salinity chain arrays, complemented by seasonal hydrographic surveys and local meteorological and tide gauge measurements. In the Bab el Mandeb experiment, moorings were concentrated along two cross-channel arrays within the strait located near the potential hydraulic control sections. The cross-channel arrays were designed to measure the net inflow and outflow transports through the Strait, their seasonal and shorter-term variability, and the hydraulic properties of the exchange flow. Three moorings were also deployed along the western slope of the Gulf of Aden to monitor the properties and intensity of the Red Sea outflow plume in relation to variations in the deep outflow through the Strait. In the Strait of Hormuz, a pair of moorings was deployed near the center of the deep outflow channel to monitor the evolution of the inflow/outflow profile and the vertical watermass structure in the strait (Fig. 1).

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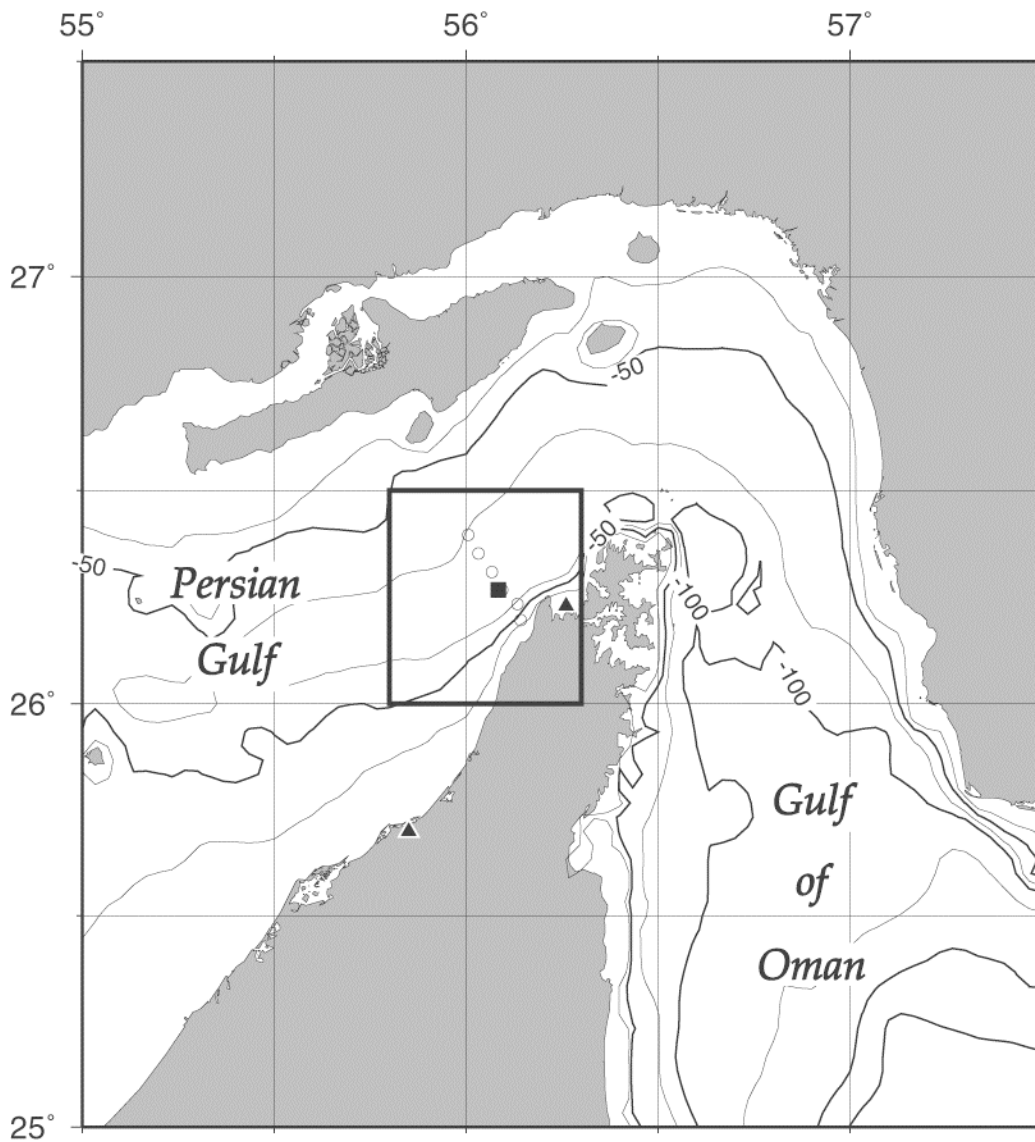


Figure 1. *The Strait of Hormuz - the study region is in the deepest part of the strait off the northwestern Musandem Peninsula of Oman. The location of the ADCP/T-S chain mooring pair (square), tide gauge (triangle) and seasonally repeated CTD stations (open circles) are indicated.*

WORK COMPLETED

Analysis of the Bab el Mandeb experimental data is well underway, with two journal articles published (Murray and Johns, 1997; Pratt et al., 1998) and several others in preparation. Observational work in the Strait of Hormuz was completed in March 1998 with successful final recovery of all mooring equipment. Processing of the Strait of Hormuz data is now complete and first results from the study were presented at the 1998 TOS meeting.

RESULTS

The Bab el Mandeb Experiment

The 18-month measurement program in Bab el Mandeb has confirmed earlier indirect estimates of an annual mean outflow of approximately 0.35 Sv of Red Sea water through the Bab el Mandeb, with substantial seasonal variation ranging from more than 0.6 Sv in winter to nearly zero in late summer. Monsoon winds over the southern Red Sea and Gulf of Aden reverse from southeasterly in winter (November-April) to northwesterly in summer (June-September), leading to strengthening and reinforcement of the two-layer thermohaline exchange during winter, and a three-layer exchange during summer consisting of weak surface and bottom outflows and an intermediate inflow. The inflow and outflow speeds appear to remain subcritical with respect to conditions for steady hydraulic control in the strait, even during the maximum two-layer exchange conditions in winter.

Synoptic transport variability through the strait on time scales from a few days to weeks is driven by two primary forcing mechanisms: wind stress variability over the strait, and variation in the large-scale barometric pressure over the Red Sea. Transport variations on these time scales can reach amplitudes of up to 0.6 Sv, nearly twice as large as the mean rate of exchange through the strait. Much of this synoptic variability can be explained by a linear, 2-layer frictional model driven by the alongstrait wind stress and a barotropic alongstrait pressure gradient (Johns et al., 1998).

Hydrographic and deep current meter measurements in the western Gulf of Aden show that the dense outflow from the Red Sea splits into two main branches just outside the strait, one running along a narrow deep channel in the northern Gulf of Aden and the second along a broader deep channel in the south. Both plume branches are seasonally active, but the northern branch is the preferred route during weak (summer) outflow. Volumetrically the southern branch is believed to be dominant pathway on an annual mean basis.

The Strait of Hormuz Experiment

The time series measurements collected in this experiment are the first long term records in the Strait of Hormuz and reveal new aspects of the flow structure and variability. Currents in the near-surface layer are highly variable and exhibit large amplitude short-term variations especially during winter (Fig. 2). Monthly current averages suggest a mean outflow through the southern part of the Strait during fall and winter and a weak residual inflow during late winter and spring. The near-surface salinity variations (not shown) are consistent with this pattern, showing lower salinity values (< 37 psu) during spring, characteristic of inflow from the Gulf of Oman.

Measured currents in the deeper part of the Strait are relatively steady and do not indicate a significant seasonal modulation of the deep outflow. However, the salinity of the deep outflow was found to vary considerably, with pulse-like events of high salinity outflow (> 40 psu) occurring during winter. On average, lower outflow salinities occurred during the spring and early summer (March-July) and higher salinities during fall and winter (August-February). The magnitude of the annual mean deep outflow of Persian Gulf water through the Strait is estimated from these observations to be 0.25 ± 0.05 Sv, implying a net evaporation rate over the Gulf of 2.4 ± 0.6 m/year.

High resolution satellite AVHRR images collected during the experiment support our in-situ observation of a seasonal reversal of the surface currents in the southern part of the Strait. Taken together, the observations suggest that the cyclonic circulation prevalent in the southern Gulf extends partially through the Strait during the fall and winter months, and involves a significant horizontal water exchange with the Gulf of Oman which is about half the magnitude of the net vertical overturning exchange through the Strait.

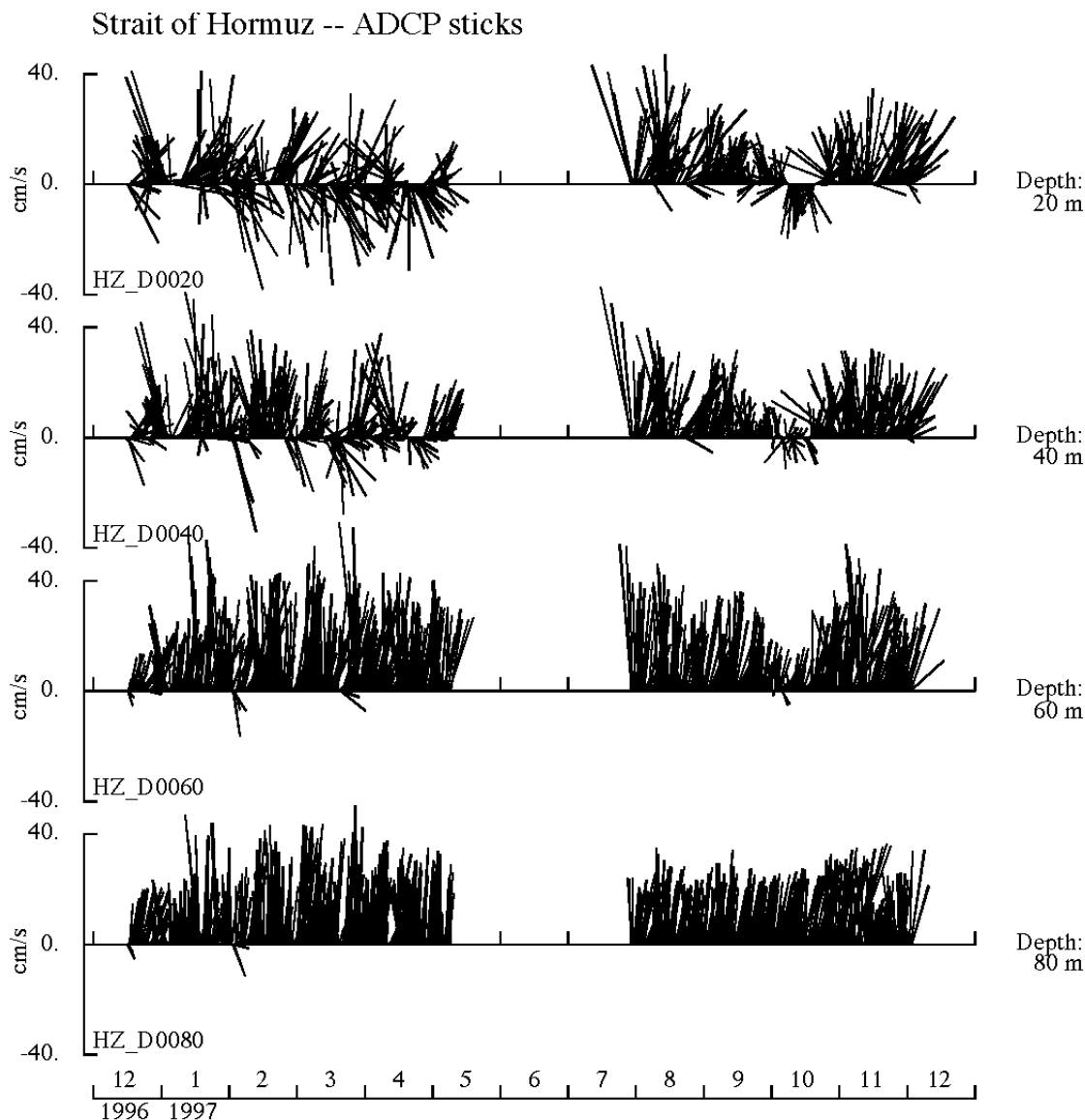


Figure 2. Vector (stick plot) time series of 40-hour low pass filtered currents at 20, 40, 60, and 80 m from the upward-looking moored ADCP in the central deep outflow channel from the Strait of Hormuz. The vectors are rotated into the along-strait direction such that up is along 55° true, representing outflow from the Strait.

IMPACT/APPLICATIONS

These observational programs have provided the first, long-term current and watermass measurements in these important straits, and should yield a new level of understanding of the relevant exchange processes and their dynamics. Comparative studies with other marginal sea straits (e.g., Gibraltar) will help to improve and broaden our understanding of the dynamical controls regulating ocean-marginal sea exchange.

TRANSITIONS

The data and results from these projects will be transitioned to the Naval Research Lab and Naval Oceanographic Office data and modeling groups to provide accurate boundary conditions for their Red Sea and Persian Gulf models and for coupling of these models to the NRL Indian Ocean model.

RELATED PROJECTS

Cooperative work with ONR P.I. Larry Pratt (WHOI) on the hydraulic characteristics of the Bab el Mandeb flow as determined from the project data is continuing. The structure of the Red Sea outflow plume in the western Gulf of Aden is being examined by combining the project data with AXBT survey data in the Gulf of Aden analyzed by ONR PI Amy Bower (WHOI). Analysis of the Strait of Hormuz moored time series data is being carried out in collaboration with U.K. investigators Howard Roe and David Smeed, who have collected extensive shipboard survey data in the strait region during the period of the moored deployments.

PUBLICATIONS

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